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I

Numerical forecasting has resulted from the drive for accuracy and objectivity in weather forecasting; it has also been furthered by joint work between meteorology--especially the theoretical dynamics of meteorology--and weather forecasting. It is one of the "two legs" of weather forecasting.

The demand for weather forecasts has increasingly grown and the objectives of forecasting have increased in number. Numerous new forecasting problems require exploration by our forecast workers. They must acquire experience, discover basic principles, and prepare their forecasts. Some relatively efficient techniques have gradually been "industrialized." Many weather forecasts are presented numerically.

In the future the relation between numerical forecasting and ordinary daily forecasting will be similar to the relation between mechanized industry and handicraft productions.

At present, researches in numerical weather forecasting not only constitute the necessary preparation for future numerical weather forecasts but also considerably aid in analyzing and explaining the physical causes of weather changes.

With this in mind, we initiated daily weather forecasts during the development of the people's meteorological enterprises, and, in 1954, we started researches in numerical weather forecasting.

II

As in other types of meteorological work, the most basic thing in numerical weather forecasting is to understand the elements of the atmospheric process. Such an understanding essentially depends on the analysis and generalization of actual atmospheric changes. The neglect of these elements would transform numerical weather analysis into metaphysics.

Of course, the area of our work is not confined to numerical weather forecasting alone. We have completed vital research in characteristics of the atmospheric process.

Hsu Erh-hao[1] was the first to study the development of the East Asian cold front, and its vorticity, extent of divergence, and distribution. In addition, he also calculated the value of each term in the humidity equation. But the result of his calculation deviated significantly from calculations made by the usual approaches.

Researches by Peiping University[2] show that, under particular conditions, the values of various terms of the vorticity equation are similar to those of the equilibrium equation. Special attention must be directed to understanding these deviations, because they suggest that methods of simplification are possible for certain basic equations, such as the vorticity equation.

As far as the existence of the eddy transport effect in large-scale general circulation is concerned, numerical analysis[3] was carried out on the basis of data obtained in February 1956. The result explained various terms of the humidity equation, in regard to the two-layer geostrophic model; the term eddy transport is very broad and it cannot be easily illustrated by the mean transport field.

Therefore, it is improper for the capitalist countries to neglect the eddy transport term or to replace it directly

by the mean transport field. All these works are necessary for establishing the corresponding models of numerical forecasting. The amount of this kind of work is still limited, and further development along this line is necessary.

III

The essential preparation for numerical weather forecasting consists of the following: on the basis of past weather experience, we apply the theory of dynamics to study some simple conditions by means of numerical analysis, so that the general characteristics of the effects of a given physical element can be obtained. For example, it is commonly known that an eddy produces quantitatively various transport effects. But eddy transport can reduce vorticity, a phenomenon similar to reduction of a high field, because the reduction process of a high field naturally causes the reduction of the relative vorticity field $\zeta \sim \nabla^2 \phi$.

It proves that the process[4]

$$\frac{\partial \zeta}{\partial t} = A \nabla^2 \zeta$$

(where A is the exchange coefficient) actually causes the reduction process

$$\phi^* = \phi + K \nabla^2 \phi$$

and

$$k = A \frac{\Delta t}{(\Delta s)^2} \qquad (1)$$

where Δt and Δs are the time and space interval, respectively. Thus, if we neglect the unnecessary small disturbances and the accumulated observation errors, cut-off errors, and other probable errors which add to the smoothing process effect, numerical weather forecasts can be

* Obykhov did similar research.

achieved with the inherent eddy effect of the model. Tsao Chi-p'ing[5] later generally analyzed these properties by means of the stability of motion.

Topography may greatly affect circulation. It plays an especially important role in China. For determining the magnitude of its effect on weather development, it is necessary to make certain calculations on the basis of assumed simple and ideal conditions. Under conditions of general west wind and north wind, graphical methods[6] were used to obtain the result of topographical effects on general barotropic circulation disturbances.

The numerical tendency results obtained indicate that the topographical disturbance is much greater than that of North America under similar conditions. Under baroclinic pressure, because of the effect of the stable layer, the topographical disturbance of the lower layer is greater.

In the mountain region of A-erh-t'ai Shan and Hsiang-t'ien Shan[7], if the mean west wind velocity is five meters per second, the high tendency at 700mb on the anterior mountain slope may exceed 40 meters in 12 hours. Besides, with barotropic models, calculations were made on the tendency of topographical disturbance in north China under general north-west circulation.[8] It was discovered that the position and intensity of Yi Chao in north China corresponded to the initial stage of north-west circulation. All these activities provide us with a conception of topographical disturbances under barotropic and baroclinic pressures in China.

Under actual baroclinic pressure, the basic force is sustained and supplied by outside heat sources. Therefore, for medium and long-range weather process forecasting, the process of how the heat sources affect the atmosphere is an important problem.

In 1957, Tsao Chi-p'ing[9] and others used the linear two-layer model to calculate the effect of heat sources under ideal conditions. They discovered that, no matter whether the heat source was considered as constant or influenced by the temperature and pressure field (reverse process), the effect of heat sources could be adjusted after five days or two weeks, implying that the temperature and pressure field lagged behind by about half a month.

But because of difficulties in designing the models, the effect of calculation with models is insufficient.

Chu Pao-chen and others[10] tried the Kibel radiation method. They introduced the factor of radiation into the linear two-layer models and finally obtained the equation of the heat source effect on the high field. Actual calculations were carried out. Of great significance is the fact that, when considering the relation (exchange coefficient) between input (heat source) and output (high field), the state of the heat source when affected by the temperature and pressure field is the same as the state when the heat source is constant.

The final basic forms of the different influences are the same. The calculation results of both situations are alike. In addition, Chu Pao-chen and others studied the instability of the sine curve and discovered that in such a situation the instability should be determined by more abundant data. All these researches provide us with a conception of the effect and the actual process when a heat source is applied to a temperature and pressure field. At the same time, it creates problems of model design.

IV

The realization of numerical forecasting depends upon actual calculation with models. Evidently a great amount of work must be done in establishing and choosing models, and in developing methods to obtain solutions. Only by means of actual calculations--the process of verifying theory by fact, may we reach a better understanding of forecasting by models.

As far as the one-layer quasi-geostrophic model of large-scale motion is concerned, graphical methods can be used in actual forecasting. For this reason, at the initial stage (1954-1956), we carried out some researches in graphical numerical forecasting.

Liao Tung-hsien[11] examined the two-layer forecast equation

$$\frac{\partial \xi}{\partial t} = -V \cdot \nabla \xi - \frac{1}{3} V_T \cdot \nabla \eta_T, \qquad (2)$$

where ξ denotes absolute vorticity, V_T denotes thermal wind, and η_T denotes the mean flow vorticity of the thermal wind. Calculation proves that the second term on the right-hand side of the equation is a relatively small correction factor.

In primary approximation, it is reasonable to assume that the correction factor varies insignificantly during the forecast period. On this basis the approximate solution can be obtained graphically according to V and V_T by manipulating the ξ and η_T field separately. Actual forecasts show that better results are attained when we apply this method to forecasts of cold front development than [when we apply it] to forecasts of the mean flow of nonthermal driven wind (barotropic model). This method is basically similar to that of Fjortofts.

Subsequently, a researcher,[12] by adapting a similar method, tested a 48-hour 500mb isobaric surface forecast. It shows that some cold fronts can be forecast 48 hours in advance. However, the blocking high pressure cold front cannot be forecasted with certainty. Besides, since the

$$V \frac{\partial f}{\partial y}$$

term is relatively small, it can be neglected if graphical solutions are applied in numerical forecasting.

Bolin used the two-layer model graphical method to obtain the solutions of the situations of both layers. Hsu Erh-hao[13] applied this method to the Sawyer and Bushby model and obtained the corresponding forecast equation, which is being verified experimentally.* Several experiments show that the results are superior to those obtained

*Recently, Hsu Erh-hao established a 1,000mb direct graphical forecast method to be published in the near future.

by using the Eliassen and Reed model. But the work involved is more complicated.

In two-layer models, a proportional decrease of temperature generally is constant. Since the upper and lower layers of the temperature field are similar, it is impossible to consider the existence of the front positon. Because of this fact, application of the general atmospheric pressure coordinate does not yield good results in forecasting weather.

Ch'en Hsiung-shan[14] and others pointed out that the existence of the front position can be considered, if the two-layer model of the position-temperature θ coordinate is used. Because the distance of the front position per equivalent surface is particularly small, we can consider the equal θ areas above and below the front position as the required layers and apply the upper and lower limits to it; in this way we are able to indicate the difference of stability both within and without the front positon. The flow field of the θ surface can thus be forecasted. They considered the upper limit θ_3 = constant and the lower limit θ_2 = constant. The positional vorticity =

$$\frac{KC_p^{1/k}\,\theta}{1{,}000} \times (\zeta + f)\left(\frac{\partial\psi}{\partial\theta}\right)^{-1/k}$$

where $K = (Cp - C\theta)/Cp$, ψ denotes the flow function of θ surface, and others are conventional symbols.

Based upon the above method, a graphical forecast was made (12 hours). The result was found to be relatively better. Yet the difficulty of this method lies in the problem of assuming the boundary conditions, especially the boundary condition of the upper limit. Proper solutions of this problem remain to be found. Besides, the existence of these front positions has not been considered in constructing models.

Besides the experiments in the graphical method, the accuracy of Fjortoft's graphical method is being studied. Fjortoft considered the difference

$$\alpha - \bar{\alpha} = h \qquad (3)$$

in Poisson's equation

$$\nabla^2 \alpha = -h$$

where $h = \frac{d^2}{4} h$, $\bar{\alpha}$ is the mean value of α inside the rectangle and d denotes the interval of the rectangle. Then the solution is

$$\alpha = (1 + M + M^2 \ ....)h. \qquad (4)$$

It is accurate only if an infinitive region is assumed. Fjortoft proved that

$$\alpha^* = h + 2\bar{h} \qquad (5)$$

can be considered as the first approximate solution of (3).

Ch'ou Chi-fan[16] and others, in thirty experiments, proved that error in using

$$\alpha = h + 2\bar{h}$$

is within the permissible degree of accuracy of the graphical method. But h consists of the vorticity mean circulation. It is obtained by graphically extrapolating the mean circulation in space. But based upon the same experiment, with the distance of the mean circulation rectangle d = 600 millimeters, the change of value is as large as two thirds the original circulation field. The result is therefore unsatisfactory.

The graphical method for numerical forecasts of rain is also necessary. Chang Yen[17] suggested a synthetic process for large-scale short-range numerical forecasts of rain. Particular examples were chosen for purposes of calculation, and the results were good. The method is worthy of further investigation and improvement.

For accurate numerical forecasts, the use of electronic computers is necessary; hence, the finite differential method is used. In this connection, one should transform

the differential equations of numerical weather forecasts into differential equations for further calculation. A large number of techniques are used in all these numerical calculations, which involve the width of the rectangle, the interval of time, and the problem of extrapolation of time. Since no actual calculation has been performed by electronic computers, no final conclusion has been drawn, as yet, in this respect.

As far as Poisson's approximation method is concerned, Ku Chen-tsao[18] used the least square method and a finite number of the mean value terms M to obtain the approximate solution of equation (3). He proved that, when choosing h and $\bar{h}$, the best approximation form is

$$\alpha^* - 0.4h + 4.4\,\bar{h}, \qquad 4 \leqslant 2/d \leqslant 12; \qquad (6)$$

This is more accurate than Fjortoft's form $\alpha^* = h + 2\bar{h}$ or

$\alpha^* = h + 3\,\bar{h}$. It is also simpler and more accurate than Belousov's

$$\alpha^* = (\tfrac{3}{2}h + 2\bar{h} + \bar{\bar{h}}). \qquad (7)$$

It is convenient to use approximate formula (6) in electronic calculations. For a higher degree of precision, similar methods can be used to obtain that mean value of h which may yield the best approximation formula.

The degree of precision of the graphical method is limited. In general, it is much more accurate to use the numerical approximation solution of the vorticity equation. But the application of different methods of numerical approximation involves problems of the amount of work, the degree of accuracy, and the stability.

Therefore, it is necessary to study further the problems of obtaining solutions to the vorticity equation. A Mathematics Institute team[19] found the circulation coefficient α of Blinova's barotropic linear forecast equation as a logarithmic solution in terms of time t by transforming the original differential equation into an integral equation under conditions of a longitudinal function.

Another method of solution[20] has also been considered. It is worthy of serious consideration and experimental verification.

Like the graphical method, when manipulating extrapolation, the one-layer model is the most simple to apply. Based on two twelve-hour experimental forecasts, Wang Yao-sheng and others[21] found that during the summer in China it is better to use the one-layer model for 700mb than for 500mb.

However, the one-layer model is always insufficient. For more general application, Liao Tung-hsien suggested a two-layer model to be applied to situations of particular distribution of vertical motion. He divided the atmosphere into two layers, which were described separately by a two-layer model. From this two - layer model, the three-layer model forecast equations were derived.

It is convenient to obtain the solutions graphically from these equations. A weather bureau team found an infinite series solution for the two-layer model forecast equation expressed in terms of spherical coordinates.

In certain situations, the three-layer models are essential. In various regions, if the temperature changes of the upper and lower layers do not assume a linearly proportional development, the use of two-layer models for weather forecasting generally is impossible.

In fact, the blocking high pressure developed in the Ural region produces the more complicated baroclinic effect[23]. Thus, three-layer models are required for forecasting.

In addition, some characteristic rules have been suggested in aplying three-parameter models[24]. For example, the special factors of the development of three-layer models can be observed from the proportionate decrease rate of the mean circulation of thermal wind. If high altitude multiple-layer weather charts are provided, the following rule can be applied to forecast qualitatively the baroclinic development, which is a particular property of the three-layer models[23]: in an extensive region the cold (warm) mean circulation increases (decreases) in strength in an upward direction;

hence, the altitude of the intermediate isobaric layer is elevated, or otherwise lowered.

Simplified estimation calculations show that, in China, topographic effects must be considered when using numerical forecast models. Nevertheless, how to describe exactly, and illustrate by models, the topographic effects remains a highly important problem.

Theoretically, Green's function can be used to solve the problems of baroclinic numerical weather forecasting under topographic influence. Unlike Sh. A. Musayelyan, who considered sea level as the boundary condition, Wang Chung-hao[25] considered the local region as the boundary condition in solving the forecast equation. The results show that Green's functions (including the integrals of Green's functions) thus obtained are regionally determined.

Hence, the value of Green's function obtained at one point is different from that obtained at another point. Though geostrophic wind is assumed, the solutions of the equations are highly complicated. It is obvious more difficult to obtain a complete solution.

Lin Hsing-yuan[26] used similar boundary conditions and suggested the Fourier Method for obtaining solutions of the forecast equations. He assumed the topographic boundary condition

$$\varsigma = 1 - \lambda\psi,$$

where ψ is proportional to the geometric topographic altitude,

$$(\varsigma = P/Po, p,$$

p denotes surface atmospheric pressure, Po denotes standard sea level atmospheric pressure). Instead of using the parameter, he expanded the solution into logarithmic series in λ, found the j-th order logarithmic forecast equation in λ, the j-th order approximation, and thus obtained the method of its solution. He denoted the vertical coordinate of the equation by

$$\varsigma = p/P$$

(where P is surface atmospheric pressure, p is high altitude atmospheric pressure), so that the lower limit

$$\varsigma = 1.$$

He applied hexagons to obtain the approximate solution of the forecast equation. The calculation also considers topographic effects. According to more than 40 examples applied in north China, a consideration of topographic effects has raised the degree of accuracy by ten percent.

Under baroclinic conditions, the problems of calculating topographic tendencies have increased in number. Two actual tendency calculations show that the accurate determination of baroclinic topographic disturbance tendency is much more complicated than previously imagined. The first problem is how to determine the surface slope wind.

If we simply consider 850mb or the upper limit boundary layer wind as the basis for calculating the vertical motion of the slope wind, we may not be able to determine the expected topographical tendency. Actually the relationship between surface wind and lower layer wind of the free atmosphere is not so simple. If we do not depend on actual observations, we find it difficult to determine the surface wind and its time rate change (wind "tendency") by using the equation of motion. If the degree of accuracy cannot be determined by actual observations, the proper choice of boundary conditions for forecast calculations may become a problem. Thus it is necessary to perform the calculations more rigorously, to gain more experience, and to delve more deeply into theoretical analysis.

V

In early 1958, with the earnest and unselfish assistance of Soviet specialist Dobryshman, who was motivated by internationalism, the Central Weather Bureau initiated medium and long-range numerical forecasting. They did much of the preparatory work,[28, 29] and attempted long-range forecasts. Keeping pace with the leap forward movement of 1958, numerical forecasting took many bold steps.

Various work groups suggested many medium and long-range linear forecast models and tested certain calculations. This is a correct beginning, because for medium and long-range forecasts, the assistance of new methods is urgently needed. It is impossible to determine the merits and defects of all models without bold experiments and practical verifications.

Chu Pao-chen suggested a two-layer geostrophic model constant heat source, as well as a geostrophic model which takes into consideration radiaktion and vortex heat (dealing with inversion caused by the temperature pressure field). The Kibel' method is followed in considering the radiation aspect (referring to the corresponding non-linear three-dimensional geostrophic model).[30] Certain properties of these models were understood after some linear calculations were carried out.

Besides, five-day forecasts and one-month forecasts were tested by using the barotropic topographic mode. Useful experiences have been obtained. All these works have helped solve the mystery of long-range numerical weather forecasting, and, by their means, experiences in calculation were obtained.

Our large-scale calculations of linear models, the results of experiments of calculations of linear models carried out by foreign countries (Blinova, Mashkovich), and the problems educed during these calculations naturally lead us to consider under what conditions the use of linear models are permissible and to consider the methods of designing the models and determining the parameters under these permissible conditions, so that the stability and superiority of the models can be guaranteed.

Researches have been conducted for this purpose. Recently new approaches have been adopted to analyze further the problem of stability of models. Relatively more general results have been obtained.[5] This greatly aids in designing linear models.

In short, this kind of work is at its initial stage. The possibilities of exploration are unlimited. Researches of similar nature can be conducted in dealing with non linear problems.

VI

Theoretically speaking, the more basic problem is not the determination of models, but the method of approach used in numerical forecasts. Since V. Bjerknes, numberical weather forecasting has been considered to be a problem of mathematics--a problem of obtaining the initial values for solving the system of partial differential equations.

That is, one should use the initial value of the first partial derivative of the meteorological quantity to find the solution of the system of differential equation. But daily weather forecasting is based on the "historical development" of the change of weather (namely the recent period, within several hours or several days).

It is similar to the long-range weather forecasting approach. Although these two approaches are completely different, but they have their own particular merits, judging from actual forecast results. The problem now is whether there is any correlation between these two approaches.

It is obviously improper to think of daily weather forecasting as simply a "deductive process," and not to give it serious consideration. As a matter of fact, under certain conditions, it is possible to prove that these two appraches are identical. For large-scale circulation under "approximation of quasi-geostrophic" conditions, Ku Chen-tsao has proved that: in considering[31]

$$\left(\nabla^2 + \alpha \frac{\partial^2}{\partial p^2}\right)\tau = \left(\frac{1}{f}\nabla^2\phi + f, \phi\right) + \frac{\alpha}{f}\frac{\partial}{\partial p}\left(\phi, \frac{\partial \phi}{\partial p}\right) \qquad (11)$$

(where ϕ is the altitude of equal pressure surface, J is the Jacobian, $\tau = \frac{\partial \phi}{\partial p}$ is the altitude tendency, α is a known parameter, P denotes pressure, and f is geostraphic parameter); the condition

$$\phi(x, y, p, t) = F(x, y, p) \qquad (12)$$

for all t $\quad p = p_0, \quad \dot{p} = 0, \quad \omega = 0 \qquad (13)$

(where t_o denotes initial time, F denotes a known function) and condition when $P = P_o$

$$\left.\begin{array}{l}\phi(x, y, p_0, t) = G_1(x, y, t), \\ T(x, y, p_0, t) = G_2(x, y, t),\end{array}\right\} (t \leqslant t_0) \qquad (14)$$

when $\quad t = -\infty \quad, \frac{\partial^2 \phi}{\partial p^2}$ = known distribution, (15)

and when $t \geqslant t - \alpha \quad, \quad p = p_0 \quad, \quad \dot{p} = 0 \quad, \quad \omega = 0 \qquad (16)$

(where $t - \alpha < t_o$) are equivalent in value. In (14) P_o can be replaced by other values of pressure $P = P_o$.

For weather forecasts within limited areas, because of the effect of sea level boundary conditions, it is necessary to revise slightly the equivalent conditions although they are basically similar.

The above-mentioned equivalent value property shows that the change of the surface temperature pressure field suggests the three-dimensional temperature pressure field structure of the baroclinic atmosphere and determines the development of the three-dimensional temperature pressure field. Because of the baroclinic property, we have to consider the "historical development" of weather when using the second approach.

But the equivalent value problem is only a particular problem. Actually these two approaches do not yield equivalent values. To state this explicitly, historical data are indispensable for any numerical weather forecast, so that errors may be reduced.

By merely observing a few differential equations we can not fully understand this problem. Numerical weather forecasting is not purely a mathemetical problem. From our experiences we understand the necessity of "historical data." Like the principle of rhythm we have experienced, the conditions of various periods in the past play a considerably important role in long-range forecasts.

Of course, as far as the general forecast problems are concerned, the most important problem is the inadequacy of observational procedure; hence, we are unable to avoid errors. Past data are abundant.

Therefore, the problem of choosing the correct approach should be based upon the availability of observation data; we should choose an approach so that available observational data can be fully utilized, and we should avoid approaches which require unavailable observational data. For this reason it is advisable to utilize data in the past, and as a matter of fact we cannot avoid using them.

However, further research is necessary on how to utilize fully the most reliable and complete distribution of meteorological data in past and recent periods, so that the most proper form of the system of weather equa-

tions, when integrating numerically with respect to time, can be chosen and the proper conditions for the solution can be determined. Researches in this respect are at their initial stage. The solution of this problem may provide a new direction for numerical weather forecasting.

* * *

Certainly, the history of the development of numerical weather forecasting in China is short. However, under the correct leadership of the Party and the State, the development of numerical weather forecasting in such a brief period has been comparatively rapid. Actually, only after the establishment of the people's meteorological enterprises,and of the complete observation and forecast system, were the foundation and necessary conditions for all the researchers provided.

During the period of reactionary rule, all these conditions were incomprehensible. Since the "leap forward movement," numerical weather forecasting in China has assumed a new appearance. It is expected that in the near future, by combining practical requirements with new technology and new theory, numerical weather forecasting will reach a higher stage.

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